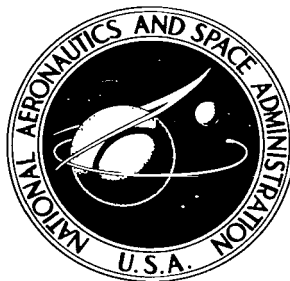


NASA TECHNICAL NOTE



NASA TN D-3131

NASA TN D-3131

LOAN COPY: RETURN
AFWL (WLIL-2)
WORTLAND AFB, N M

0130145



TECH LIBRARY KAFB, NM

DATA COMPARISONS AND
PHOTOGRAPHIC OBSERVATIONS OF
COAXIAL MIXING OF DISSIMILAR GASES
AT NEARLY EQUAL STREAM VELOCITIES

by Robert G. Ragsdale and Oliver J. Edwards

*Lewis Research Center
Cleveland, Ohio*



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION - WASHINGTON, D. C. - DECEMBER 1965

TECH LIBRARY KAFB, NM



0130145

NASA TN D-3131

DATA COMPARISONS AND PHOTOGRAPHIC OBSERVATIONS OF COAXIAL
MIXING OF DISSIMILAR GASES AT NEARLY EQUAL STREAM VELOCITIES

By Robert G. Ragsdale and Oliver J. Edwards

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 - Price \$1.00

DATA COMPARISONS AND PHOTOGRAPHIC OBSERVATIONS OF COAXIAL MIXING OF DISSIMILAR GASES AT NEARLY EQUAL STREAM VELOCITIES

by Robert G. Ragsdale and Oliver J. Edwards

Lewis Research Center

SUMMARY

An analytical and experimental study is made of the isothermal turbulent mixing that ensues when one gas is injected coaxially into a stream of another gas that is moving in the same direction at an equal velocity. The problem of turbulent coaxial mixing of dissimilar gases has been the subject of a number of recent studies. Proposed expressions for turbulent viscosity are compared in this report on a consistent basis. It is shown that the different equations predict essentially the same eddy viscosity for stream-velocity ratios from 0.76 to 2.8. Considerable divergence of results occurs, however, when a given equation is applied beyond the range of experimental conditions for which it has been verified.

The results of a photographic study of the turbulent coaxial flow of a bromine jet into an air stream are presented. Photographs of the bromine stream show that, for equal stream velocities, the flow appearance changes from laminar to turbulent as the upstream Reynolds number of the bromine stream is increased from 1840 to 3230 and the Reynolds number of the air stream is increased from 2130 to 3660. When honeycombs with 1/8-inch-diameter cells that are 2 inches long are placed in both the air stream and the bromine stream, the turbulent appearance at the higher Reynolds number is greatly reduced. Photographs of the bromine stream for initial air-to-bromine velocity ratios of 0.85 and 1.52 indicate that the turbulence created by this velocity difference is much less than that initially present in the two streams.

It is concluded that the turbulence initially present in the two streams plays an important part in the turbulent coaxial mixing of dissimilar gases at nearly equal stream velocities. It is, therefore, probable that simple, empirical modifications of Prandtl's expression for eddy viscosity do not adequately describe the mixing process and that additional terms should be included to account for the initial turbulence present in the two streams.

INTRODUCTION

Turbulent shear flow has remained a subject of interest in the field of fluid mechanics for a considerable number of years. Free turbulence most commonly occurs in jet and wake flows. Most of the initial attention to jet flow was directed to the situation where an incompressible fluid issues into a quiescent environment of the same fluid. Considerable success was achieved by the application of phenomenological theories, notably Prandtl's mixing length hypothesis, and similarity solutions (ref. 1).

A more complex situation arises when the medium into which the jet exhausts is not at rest and is not of the same material. Such a system has been the subject of a number of recent studies. These investigations have been prompted by interest in a gaseous-fuel nuclear rocket engine (ref. 2), where a low-velocity fissionable gas is injected coaxially into a high-velocity hydrogen propellant stream, and by interest in a supersonic combustor (ref. 3), where high-velocity hydrogen issues into a parallel stream of oxidizer that is flowing at a comparable velocity. Both situations involve the turbulent coaxial mixing of dissimilar gases.

Up to a point, the approaches to the problem of coaxial mixing of dissimilar gases have been the same. The diffusion equation and the Navier-Stokes momentum equations are written for isothermal, axisymmetric, boundary-layer flow, along with the continuity equation. This equation set is then applied to turbulent flow by assuming that the molecular transport coefficients can be replaced by or added to their turbulent counterparts. These equations are then solved by a transformation to a stream-function, axial-coordinate plane. All of the theoretical works have assumed that the turbulent transport coefficients are constant in the radial direction. An experimental study of hydrogen, helium, and argon jets issuing into an air stream indicates that this assumption is reasonably good; the eddy viscosity was found to decrease to 0.8 of the centerline value at the half-radius of the jet (ref. 4).

To complete the analytical description of the flow field, it is necessary to make some algebraic statement as to the dependence of the eddy viscosity and the eddy diffusivity on pertinent geometry, flow, and physical-property parameters. It is in this regard that various approaches have been suggested. What is required is the equivalent of Prandtl's hypothesis, which stated that, in a region of free turbulence, the eddy diffusivity is proportional to the width of the mixing zone and to the difference between the maximum and minimum velocities across it.

Two problems arise if this formulation is applied as stated. The first is that no turbulence is predicted for the case of equal stream velocities, although it has been observed in experimental studies. It has been demonstrated, however, that an eddy viscosity proportional to a velocity difference can be used to correlate turbulent coaxial mixing of dissimilar gases if the stream velocities are not equal (refs. 5 and 6). A pro-

posals have been made for the situation of nearly equal stream velocities to modify Prandtl's original hypothesis to include the difference in stream densities. One suggestion is to replace the velocity difference with a mass flux difference (ref. 3); such a formulation has shown agreement with experimental data over the ranges investigated. This expression, however, is not altogether satisfactory, since it predicts no turbulence when the mass fluxes of the two streams are equal. An experimental study of this particular flow condition (ref. 7) has shown that turbulence does exist for equal mass fluxes; the author of reference 7 proposes an expression to eliminate this anomaly, in which the eddy viscosity is taken to be proportional to the sum of the mass flux and the momentum flux. This expression is also shown to be in agreement with some experimental data.

The second problem that arises in attempting to apply Prandtl's free-turbulence expression to the coaxial mixing process results from the fact that it attempts to attribute all turbulence to the velocity difference between the two streams. The original equation, as well as all of the proposed modifications discussed previously, requires that the eddy viscosity in the coaxial mixing region be proportional to some difference between the two streams. This does not account for any turbulence that is initially present in either of the two streams. It has been suggested that this "preturbulence" may be the dominant factor if the two streams are at nearly equal velocities (ref. 8). The possible contribution of initial stream turbulence and boundary layers has also been mentioned in a number of the recent studies (refs. 3, 5, and 7). In a study of the similarity of velocity profiles in ducted jet flows, honeycombs were found to be effective in reducing "preturbulence" introduced into the system along with the ambient air (ref. 9). This is in accord with studies of the effect of grids on the eddy-diffusion coefficient in turbulent duct flow, where it has been found that grids appreciably reduce the scale of turbulence (ref. 10).

These two aspects, eddy viscosity correlations and preturbulence, of the turbulent coaxial mixing of dissimilar gases have been investigated and are discussed herein. A number of expressions have been proposed for the eddy viscosity variation. Though the algebraic formulations (refs. 3, 5, and 7) appear to have significant differences, each expression has shown agreement with experimental data, at least for the range of data investigated in each case. These various relations for eddy viscosity are compared here on a consistent basis in order to disclose their similarities and differences. Previously published data (ref. 5) are compared with theoretical calculations in order to determine the axial dependence of the eddy viscosity. The theoretical calculations are made with a computer program (refs. 2 and 11) that solves the axisymmetric boundary-layer equations with no similarity assumptions and incorporates arbitrary variations of eddy viscosity in the axial direction. The data of reference 5 are compared with the analysis for an eddy viscosity that either increases, decreases, or is constant with axial position.

Results are also presented for a photographic study of the effect of preturbulence on

the coaxial mixing process at nearly equal stream velocities. Photographs of a bromine stream exhausting into a surrounding air stream for various flow conditions are shown. The initial velocity ratios, air to bromine, were maintained between 0.99 and 1.01 to minimize the contribution of velocity difference to the free turbulence. Air and bromine Reynolds numbers were varied from 2130 to 3660 and from 1840 to 3230, respectively. These flow conditions were repeated with 1/8-inch-passage-diameter honeycomb sections 2 inches thick in both the air and the bromine streams at the injection point. In order to determine the relative contribution to turbulence of a velocity difference, initial-velocity ratios were varied from 0.85 to 1.5 at a constant bromine Reynolds number of 2300.

SYMBOLS

A, B, C	constants
C^*	normalized average bromine concentration
D_{12}	binary diffusion coefficient
R	hydraulic radius
Re	Reynolds number, $2RU\rho/\mu$
r	radial coordinate
$r_{1/2}$	half-radius
U	axial-velocity component
z	axial coordinate
\bar{z}	dimensionless axial distance, z/r_j
ϵ	eddy diffusivity
$\rho\epsilon$	eddy viscosity
μ	viscosity
ρ	density

Subscripts:

c l	centerline
e	external
j	jet

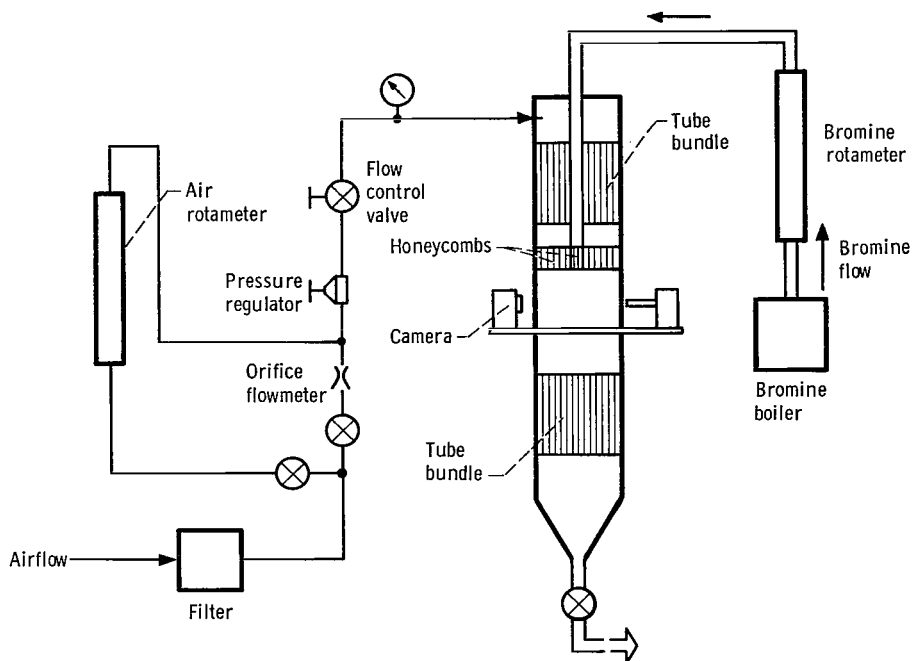


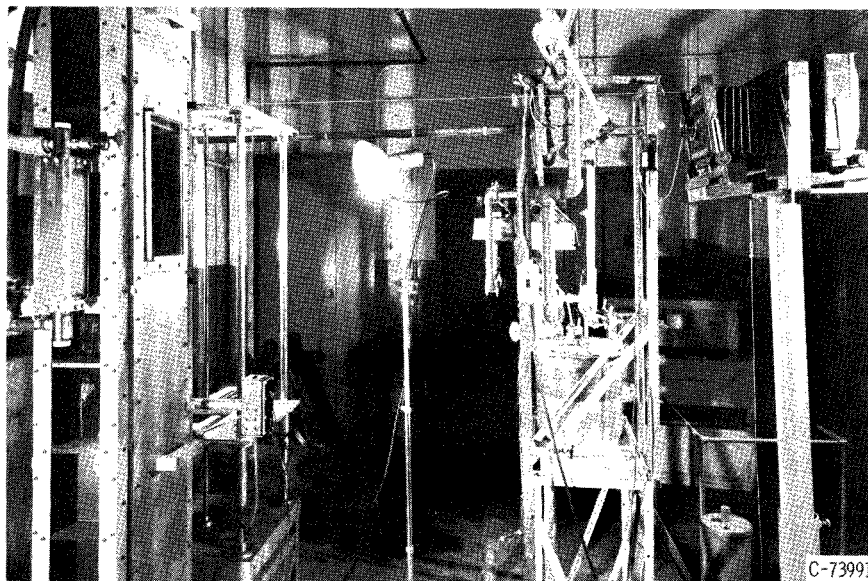
Figure 1. - Schematic drawing of air-bromine system.

EXPERIMENTAL APPARATUS AND PROCEDURE

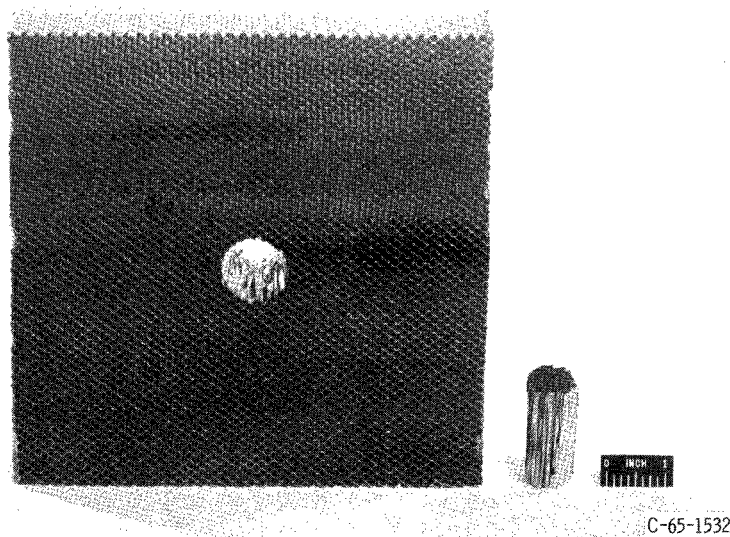
Figure 1 shows a schematic diagram of the experimental apparatus, a larger and more versatile version of the test chamber described in reference 5. The central feature of this apparatus is the rectangular vacuum-tight test section, which is 8 inches square in cross section by approximately 9 feet in height. Figure 2(a) (p. 6) shows a photograph of this test section and some of the associated instrumentation.

The bromine boiler is seen at the right in figure 2(a); bromine flow is controlled by the power input to an internal quartz-jacketed pancake heater immersed in the bromine liquid. The test section is operated at the vapor pressure of room-temperature bromine, about 4.5 pounds per square inch absolute. The heater replaces the heat of vaporization at a rate sufficient to maintain the desired evaporation rate, or bromine flow. The Monel boiler is coated inside with Teflon. Because of the extreme corrosiveness of bromine, only glass or Teflon is in contact with the bromine until it reaches the top of the test section. There it enters a 1-inch-diameter (0.933-in. i.d.) Monel tube, feathered at the injection end, from which it enters the air stream. Both gases flow from top to bottom through the test section. Flow rates are measured by rotameters, calibrated to within $\pm 1/2$ percent; chamber pressures are read from a mercury manometer.

The honeycomb inserts used to reduce preturbulence are shown in figure 2(b). The



(a) Flow apparatus.



(b) Honeycomb inserts.

Figure 2. - Experimental setup.

TABLE I. - FLOW CONDITIONS FOR PRETURBULENCE STUDY

Figure	Run	Velocity ratio, U_e/U_j	Jet Reynolds number, Re_j	External Reynolds number, Re_e	Honey-combs	Average jet velocity component, U_j , ft/sec	Average external velocity component, U_e , ft/sec
7(a)	E1	1.01	1840	2130	No	2.9	2.9
7(b)	E6	.99	3230	3660	No	5.1	5.0
7(c)	E25	1.01	^a 1840	^a 2130	Yes	2.9	2.9
7(d)	E27	.99	^a 3230	^a 3660	Yes	5.1	5.0
7(e)	E3	.99	2300	2600	No	3.6	3.6
7(f)	E12	.85	2300	2240	No	3.6	3.1
7(g)	E11	1.52	2300	4010	No	3.6	5.5

^aReynolds number based on channel dimensions upstream of honey-combs in order to emphasize that flow conditions are identical except for presence of honeycombs.

larger insert in the air stream was positioned by means of small support tabs in the corners of the test section. The smaller honeycomb was force-fitted in the end of the bromine tube. The downstream surfaces of the honeycomb and the end of the bromine tube were in the same plane. Although both honeycomb surfaces immediately adjacent to the bromine tube were somewhat rough, this introduced no appreciable turbulence into the free jet region. This was shown by tests to be described in the section Discussion of Results; flow that was steady and laminar in appearance was unchanged by the addition of honeycombs. Lucite tube bundles at the top and bottom of the test section eliminated any large-scale flow oscillation in the air stream.

The first step in the running procedure is to set the desired air flow rate. This is done by use of an upstream flow-control valve and a downstream valve that throttles to a vacuum exhaust system. After the desired air flow is established, at the vapor pressure of bromine, the bromine flow is initiated by supplying power to the boiler.

Photographs of the bromine flow at the injection point were taken with a stroboscopic lamp, with a 1/6000-second exposure, to show the individual eddies in the mixing region. In figure 7 (p. 14), the end of the bromine injection tube is just at the top of the photograph.

All Reynolds numbers cited are based on the hydraulic diameter of the flow channels at the injection point. Table I lists the flow conditions for the photographs taken. To emphasize that flow rates are unchanged between figures 7(a) and (c) and figures 7(b) and (d), the same Reynolds numbers are listed. The presence of the honeycomb, of course, decreases the local Reynolds numbers; for figures 7(c) and (d), the bromine honeycomb Reynolds numbers are 1/8, and the air honeycomb Reynolds number 1/64, of those in figures 7(a) and (b).

THEORETICAL CONSIDERATIONS

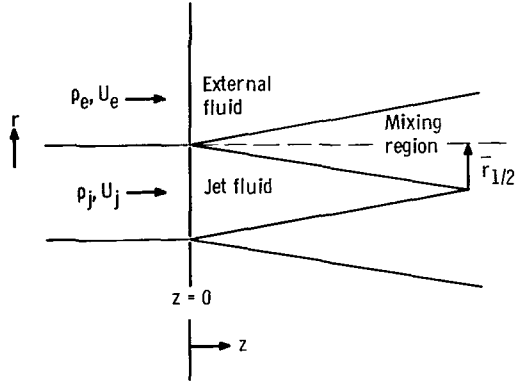


Figure 3. - Model of coaxial flow system.

The basic analytical procedure used here to compute turbulent coaxial velocity distributions is described in references 2, 5, and 11, and only the pertinent features will be discussed here. The equation set is composed of the continuity, diffusion, and momentum equations written for isothermal, axisymmetric, boundary-layer flow. The buoyancy term is included, and no linearizing or similarity assumptions are made so that the results apply equally well near the jet origin. A

von Mises transformation to a stream-function axial-position coordinate set is employed in the numerical solution. The ratio of eddy viscosity to molecular viscosity $\rho\epsilon/\mu$ is assumed constant in the radial direction and is varied in the axial direction according to the arbitrary function $A + B(\bar{z})^C$, where \bar{z} is the axial distance, measured in jet radii, from the jet origin. The turbulent transport coefficients, $\rho\epsilon$ and ϵ , are added to their molecular counterparts, μ and D_{12} , respectively. The eddy diffusivities for momentum and mass transport are assumed equal. The model of the coaxial flow field and the pertinent variables are shown in figure 3.

If the various expressions for eddy viscosity are to be compared, they must be rewritten in the same form. From a study of air-bromine coaxial mixing, reference 5 obtains the following equation:

$$\left(\frac{\rho\epsilon}{\mu}\right)_{cl} = 0.0172 \left| \frac{U_e}{U_j} - 1 \right|^{1/2} (\text{Re}_j - 250) \quad (1)$$

For Reynolds numbers that are large with respect to the constant 250, equation (1) can be written in the form

$$\frac{(\rho\epsilon)_{cl}}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e}\right) = 0.187 \left| \frac{U_e}{U_j} - 1 \right|^{1/2} \quad (2)$$

In equation (2), $(\rho\epsilon)_{cl}$ is the centerline value of the eddy viscosity.

Reference 3 suggests the following expression for eddy viscosity:

$$(\rho\epsilon)_{cl} = 0.025 r_{1/2} (\rho_e U_e - \rho_c U_{cl}) \quad (3)$$

where $r_{1/2}$ is the radius to midpoint of the mixing region, as shown in figure 3. When both sides are multiplied by (ρ_j/ρ_e) , equation (3) can be written at the jet origin as

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e} \right) = 0.025 \left(\frac{U_e}{U_j} - \frac{\rho_j}{\rho_e} \right) \quad (4)$$

This expression has shown agreement with air-hydrogen data. For equal temperatures, the density ratio on the right side of equation (4) becomes the ratio of hydrogen to air molecular weight, 0.069. It should be noted here that the preceding expression produces an eddy viscosity ratio that varies in the axial direction, since both the centerline density and the velocity are axial functions. For the purposes of this comparison, equation (4) is used to evaluate the eddy viscosity at the jet origin, where the jet density and velocity are at their initial values.

The expression proposed in reference 7 for the eddy viscosity is as follows:

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} = 0.025 \frac{r_{1/2}}{r_j} \left(\frac{\rho_e U_{cl}}{\rho_j U_j} + \frac{\rho_e U_e^2}{\rho_j U_j^2} \right) \quad (5)$$

This equation can be written in a form similar to equations (2) and (4) at the jet origin:

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e} \right) = 0.025 \left[1 + \left(\frac{U_e}{U_j} \right)^2 \right] \quad (6)$$

where $(\rho\epsilon)_c l$ is the value of the eddy viscosity in the jet stream at the injection point.

Equations (1), (3), and (5) have all been proposed to express the functional dependence of the turbulent viscosity $\rho\epsilon$. Obviously, they are not of the same form; yet each has been shown to agree with experimental data. By rewriting the equations in the forms given by equations (2), (4), and (6), it is possible to compare the various expressions on a consistent basis to see how similar or different they are.

In reference 5 it is suggested that a molecular viscosity ratio of the two streams should be included in the expression for eddy viscosity. In order to evaluate this idea, equations (2), (4), and (6) can be rewritten by multiplying by the viscosity ratio on the left side of the equations and multiplying the numerical coefficients on the right side by the actual values of the viscosity ratios of the gases used in the experiments related to each expression. By using the viscosity ratios of the gases studied by each of the investigators, equations (2), (4), and (6) can be written as follows:

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e} \right) \left(\frac{\mu_e}{\mu_j} \right) = 0.228 \left(\frac{U_e}{U_j} - 1 \right)^{1/2} \quad (7)$$

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e} \right) \left(\frac{\mu_e}{\mu_j} \right) = 0.051 \left(\frac{U_e}{U_j} - \frac{\rho_j}{\rho_e} \right) \quad (8)$$

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e} \right) \left(\frac{\mu_e}{\mu_j} \right) = 0.051 \left[1 + \left(\frac{U_e}{U_j} \right)^2 \right] \quad (9a)$$

$$\frac{(\rho\epsilon)_c l}{\rho_j U_j r_j} \left(\frac{\rho_j}{\rho_e} \right) \left(\frac{\mu_e}{\mu_j} \right) = 0.031 \left[1 + \left(\frac{U_e}{U_j} \right)^2 \right] \quad (9b)$$

Equations (9a) and (9b) are both rewritten forms of equation (6) with viscosity ratios of hydrogen - air and carbon dioxide - air, respectively, since both of these systems were studied in reference 7. The viscosity ratios of bromine - air, hydrogen - air, and carbon dioxide - air, were taken to be 1.22, 2.04, and 1.24, respectively.

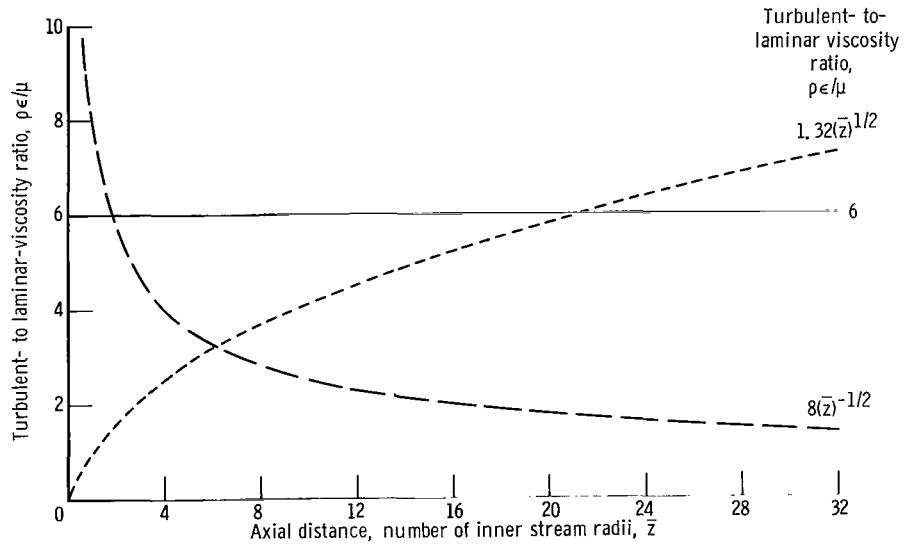


Figure 4. - Variations of turbulent-to-laminar viscosity ratio used in data comparison for velocity ratio of 1.25, jet Reynolds number of 870, and external Reynolds number of 1720.

DISCUSSION OF RESULTS

In reference 5 it was shown that good agreement between theory and experimental data was obtained by assuming that the ratio of turbulent to laminar viscosity $\rho\epsilon/\mu$ was constant over the entire flow field. Since for the air-bromine system studied, the viscosity ratio was only 1.22, this assumption also results in an eddy viscosity $\rho\epsilon$ that is essentially constant. In references 3 and 7, the proposed expressions (eqs. (3) and (5)) yield an eddy viscosity that varies in the axial direction. To check the importance of an axial dependence of eddy viscosity, the data reported in reference 5 have been compared with the analysis of reference 11. The arbitrary variations of $\rho\epsilon/\mu$ considered are shown in figure 4. The constant value of 6 is the one reported in reference 5 as best representing the experimental data for an initial air- to bromine-velocity ratio of 1.25, a bromine Reynolds number of 870, and an air Reynolds number of 1720. The other two variations considered were a turbulent- to laminar-viscosity ratio that is proportional to $(\bar{z})^{1/2}$ and one that is proportional to $(\bar{z})^{-1/2}$. The coefficients shown for these two cases are those that best represented the data from reference 5 shown in figure 5 (p. 12). Figure 5(a) shows the comparison of the experimental data of reference 5 with theory for the three cases. The ordinate is the average bromine concentration normalized to the first data point. Figures 5(b) and (c) show similar comparisons for initial-velocity ratios of 0.97 and 0.83.

These results indicate that, although an axial variation of the turbulent- to laminar-viscosity ratio does fit the data, it is not necessary. A constant value is adequate, if not better. This is in accord with the case of a circular jet issuing into a quiescent environment of the same fluid; for this situation, it has been established that the kinematic eddy viscosity is indeed constant over the entire flow field (ref. 1).

Figure 6(a) (p. 13) shows a comparison of the various expressions for the turbulent viscosity as given by equations (2), (4), and (6). The data points on the curves from references 3 and 7 indicate the velocity ratios at which the analysis has been compared with experimental data. With the exception of the point at a velocity ratio of 2.8 (from ref. 3), the various expressions are in general agreement. This is quite remarkable, in view of the differences in the algebraic formulations and the wide variations of the experimental conditions upon which they are based. The expressions of references 5 and 7 predict turbulent viscosities at the jet origin that are quite close; the data of reference 5 were obtained with an air-bromine system and jet Reynolds numbers from 255 to 3850, while the data of reference 7 were for a hydrogen - air and a carbon dioxide - air system at jet Reynolds numbers of the order of 1 million. The limits of ± 25 percent shown indicate the spread of the data of reference 5. It is of interest to note that the agreement between the expressions of references 5 and 7 would not exist at velocity ratios beyond about 3.5. The correlation of reference 7 predicts turbulent viscosities that are consid-

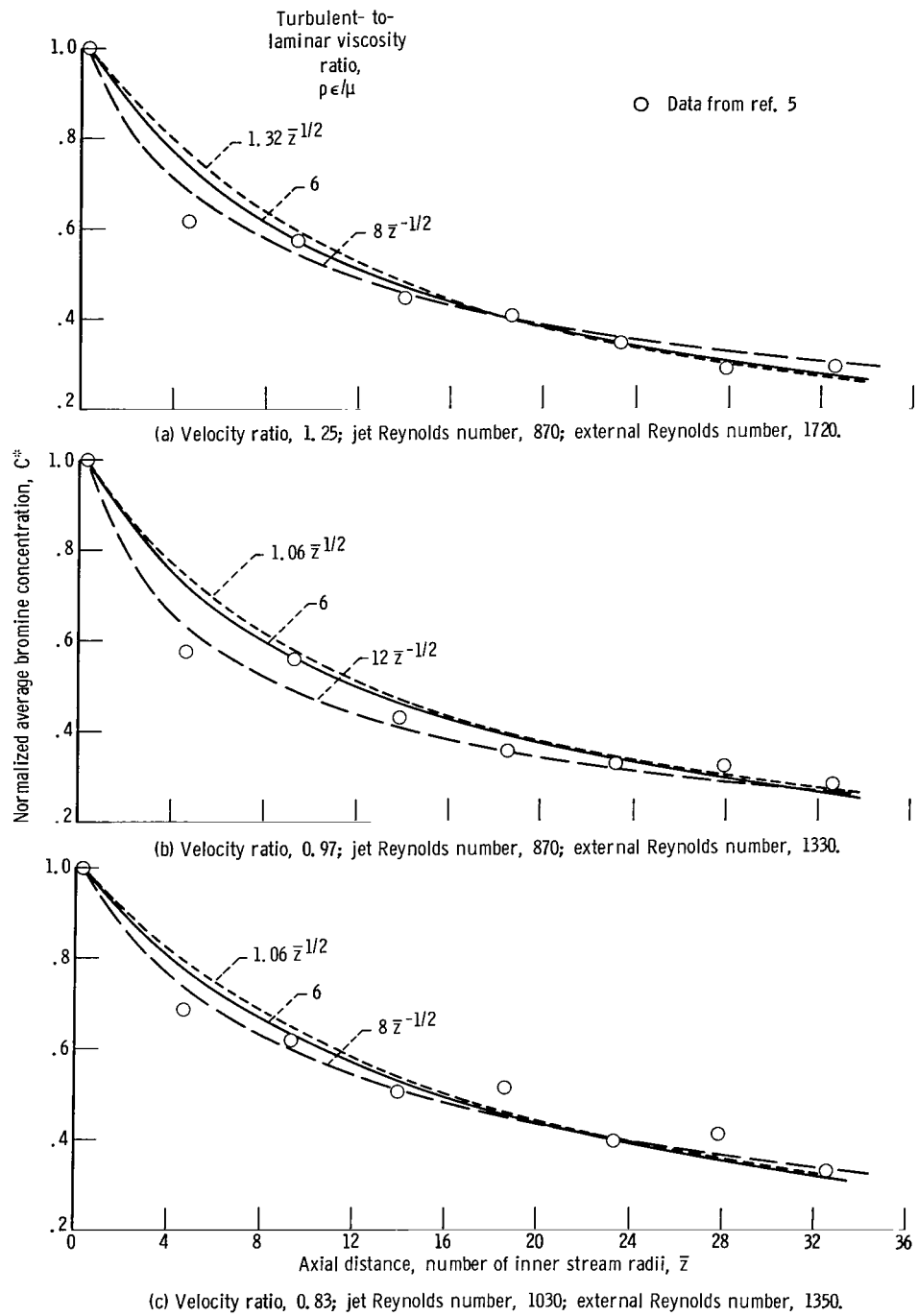


Figure 5. - Comparison of data and analysis.

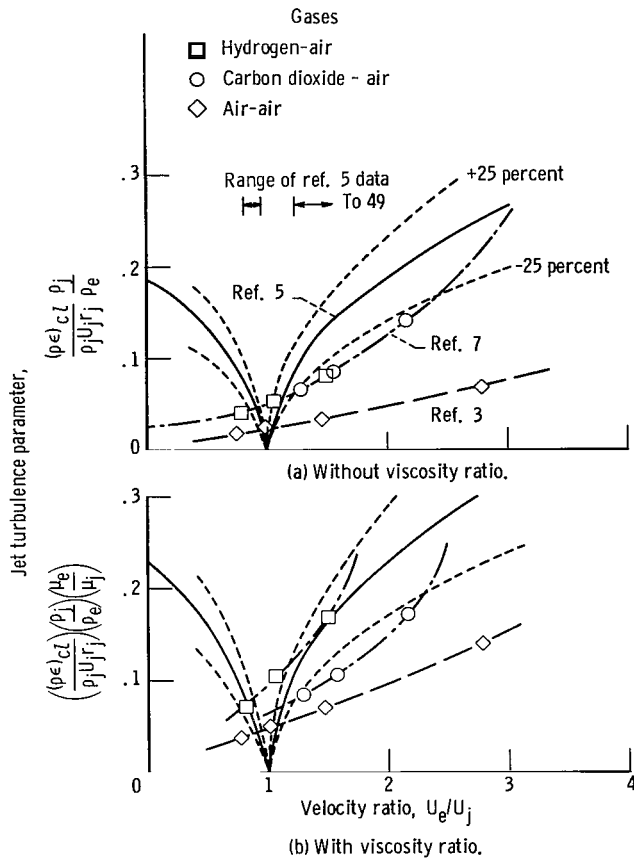


Figure 6. - Comparison of turbulent viscosity formulations at jet origin.

erably in excess of those measured in reference 5, if the equation is applied much beyond the range in which it has been experimentally verified. This is due to the contribution of the momentum flux term in equation (5), which contains a squared velocity term.

Figure 6(b) shows a similar comparison except that the viscosity ratio of the two streams is included, as given by equations (7), (8), and (9). The trend is to move the expressions closer together, but the effect is slight, since the viscosities of the gases involved do not differ greatly.

The general conclusion suggested by figure 6 is that the modifications of Prandtl's original formulation that have been obtained by introducing mass and/or momentum fluxes have resulted in expressions that are more different in algebraic structure than in actual numerical fact.

Since considerable effort has been devoted to correlating the eddy viscosity in coaxial mixing, it is pertinent to inquire into how much of this free turbulence is actually induced by some differences between the two streams and how much upstream turbulence is carried into the free jet region. At nearly equal stream velocities the contribution of the preturbulence should be more readily detected. A series of test runs was made on a bromine jet exhausting into an air stream to investigate this effect. Photographs were taken of the bromine stream for a number of flow conditions, both with and without honeycomb sections in the two streams. Table I (p. 7) summarizes the conditions for which photographs were obtained.

Figure 7(a) (p. 14) shows the bromine flow for an initial-velocity ratio of 1.01, a bromine Reynolds number of 1840, and an air Reynolds number of 2130. This clearly demonstrates that, at nearly equal stream velocities and low Reynolds numbers, a segregated laminar-like flow pattern exists. Figure 7(b) shows the flow pattern for a velocity ratio of 0.99, a bromine Reynolds number of 3230, and an air Reynolds number of 3660. Here the nature of the flow is markedly turbulent, though the velocity ratio is essentially unchanged. This shows that, for these flow conditions, turbulence can be induced in the

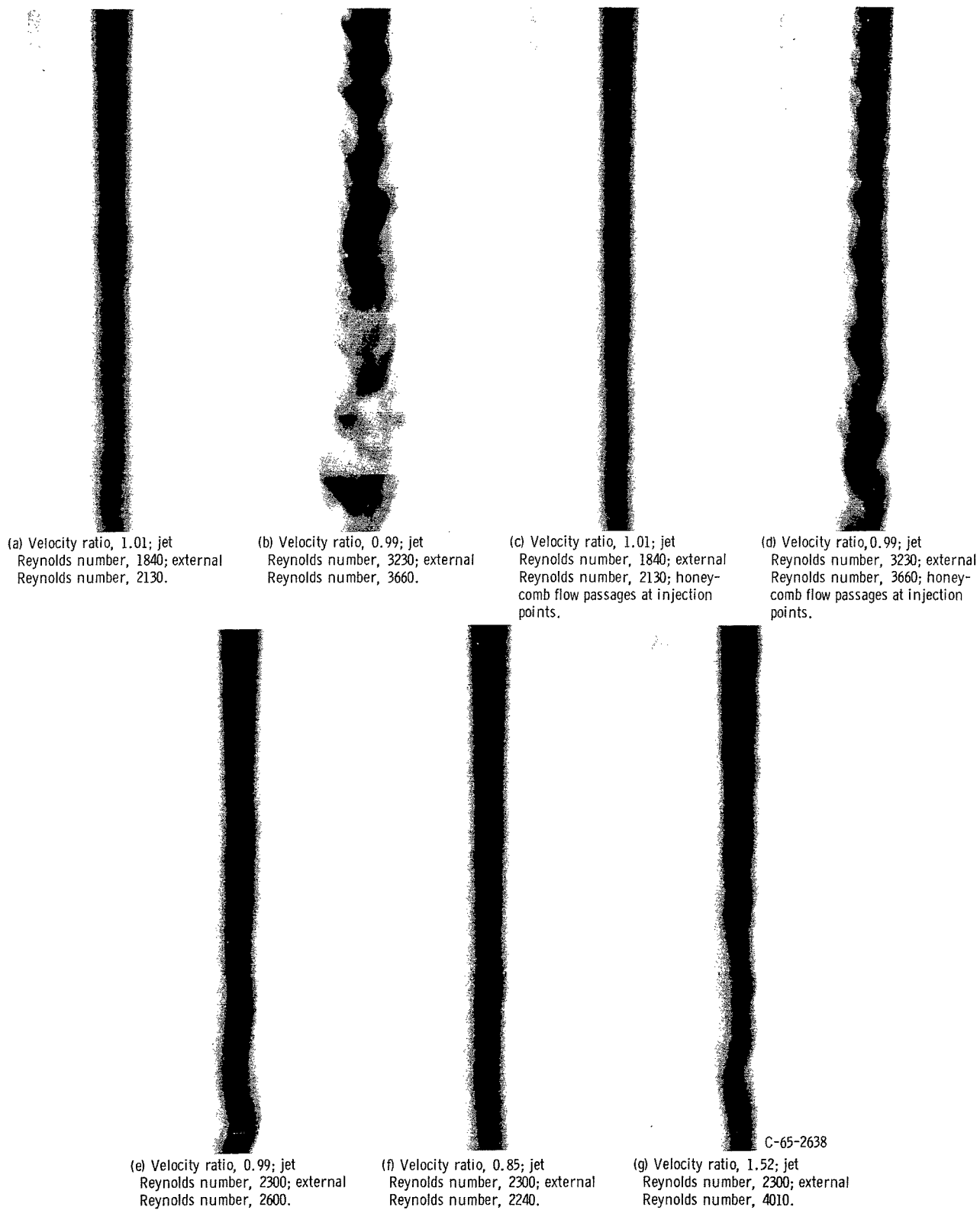


Figure 7. - Flow patterns.

coaxial mixing region by increasing the stream Reynolds numbers at constant velocity ratio.

To study the effect of upstream turbulence further, these flow conditions were repeated with honeycomb flow passages in both the air stream and the bromine stream at the injection point. An individual passage in the honeycomb was $1/8$ inch in diameter and 2 inches in length. Thus, the Reynolds number of the bromine stream in the injection tube was reduced by a factor of 8 upon entering the honeycomb, while the air Reynolds number in the upstream channel was reduced by a factor of 64.

Figure 7(c) illustrates the flow patterns at the same air and bromine flow rates as figure 7(a), but with honeycombs. This simply shows that the presence of the honeycombs did not add any significant degree of turbulence due to imperfections on downstream wakes, since a smooth, segregated flow was again obtained. Figure 7(d) shows the nature of the flow when the Reynolds numbers of the flow are increased as before. Here the flow appearance is turbulent, but the level of the turbulence is, qualitatively, much less. Comparison of figures 7(b) and (d), which are for identical flow conditions except for the honeycombs, shows that the honeycombs do significantly reduce the initial turbulence, though in this case they have not completely eliminated it.

To assess the contribution of a stream-velocity difference to turbulence relative to that initially present, the air-stream velocity was varied while the bromine-stream velocity was kept constant. In this series of runs, no honeycombs were present. Figure 7(e) again shows the laminar-like flow pattern for a velocity ratio of 0.99, a bromine Reynolds number of 2300, and an air Reynolds number of 2600. Figure 7(f) shows the flow pattern when the air Reynolds number is decreased to 2240, and the velocity ratio to 0.85. There is no significant change in the appearance of the flow. Figure 7(g) illustrates the flow pattern when the air flow is increased to a Reynolds number of 4010 and the velocity ratio to 1.52. Some flow disturbances are apparent, but the turbulence is considerably less severe than that present at a higher bromine Reynolds number and a velocity ratio of 0.99 (fig. 7(b)). This shows that the change in the nature of the flows illustrated in figures 7(a) and (b) is not due to some small variation in initial-velocity ratio.

These flow studies indicate that initial turbulence plays an important part in the nature of coaxial mixing of dissimilar gases and at nearly equal stream velocities can dominate the situation. It is therefore unlikely that expressions which contain only differences of stream parameters will meet with general success and that additional terms will be required to account for the additional sources of turbulence present in the two streams.

CONCLUSIONS

A comparison has been made of various suggested expressions for the eddy viscosity in a turbulent coaxial flow system. Some arbitrary variations of the axial dependence of eddy viscosity have been used to compare theory with published data, and a photographic study of the effect of initial stream turbulence on the mixing region has been conducted. For the range of conditions investigated, the following conclusions are indicated:

1. An axial variation of eddy viscosity does not improve the agreement of theory with experimental data over that which is obtained with a constant value.
2. Modifications of Prandtl's hypothesis for turbulent shear flow that introduce mass and/or momentum fluxes rather than velocities produce expressions whose differences are more apparent than real. These various expressions predict essentially the same eddy viscosity at the jet origin when compared at the same velocity ratio, as long as they are only applied within the range of conditions for which they have been experimentally verified.
3. The initial turbulence present in the two streams contributes significantly to the coaxial mixing process and can dominate the situation for nearly equal stream velocities. The presence of honeycomb sections immediately upstream of the injection point can reduce the turbulent mixing induced by this preturbulence.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 21, 1965.

REFERENCES

1. Schlichting, H.: Boundary Layer Theory. Fourth ed., McGraw-Hill Book Co., Inc., 1960, ch. XXIII.
2. Ragsdale, Robert G.; and Weinstein, Herbert: On the Hydrodynamics of a Coaxial Flow Gaseous Reactor, Rept. No. TID 7653, pt. 1, 1963, pp. 82-88.
3. Ferri, A.; Libby, P.A.; and Zakkay, V.: Theoretical and Experimental Investigation of Supersonic Combustion. High Temperatures in Aeronautics, C. Ferrari, ed., Pergamon Press, 1964, pp. 55-118.
4. Zakkay, Victor; Krause, Egon; and Woo, Stephen D.L.: Turbulent Transport Properties for Axisymmetric Heterogeneous Mixing. AIAA J., vol. 2, no. 11, Nov. 1964, pp. 1939-1947.

5. Ragsdale, Robert G.; Weinstein, Herbert; and Lanzo, Chester D.: Correlation of a Turbulent Air-Bromine Coaxial-Flow Experiment. NASA TN D-2121, 1964.
6. Libby, Paul A.: Theoretical Analysis of Turbulent Mixing of Reactive Gases With Application to Supersonic Combustion of Hydrogen. ARS J., vol. 32, no. 3, Mar. 1962, pp. 388-396.
7. Alpinieri, Louis J.: Turbulent Mixing of Coaxial Jets. AIAA J., vol. 2, no. 9, Sept. 1964, pp. 1560-1567.
8. Abramovich, G.N.: The Theory of Turbulent Jets. M.I.T. Press, 1963, p. 153.
9. Curtet, R.; and Ricou, F.P.: On the Tendency to Self-Preservation in Axisymmetric Ducted Jets. J. Basic Eng. (Trans. ASME), ser. D, vol. 86, no. 4, Dec. 1964, pp. 765-776.
10. Hinze, J.O.: Turbulence. McGraw-Hill Book Co., Inc., 1959, pp. 340-342.
11. Weinstein, Herbert; and Todd, Carroll A.: A Numerical Solution of the Problem of Mixing of Laminar Coaxial Streams of Greatly Different Densities - Isothermal Case. NASA TN D-1534, 1963.

302/85
/

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546